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NONLINEAR MECHANICS OF UNSTABLE PLASMAS AS RELATED TO HIGH ALTITUDE AERODYNAMICS

UNIVERSITY OF MARYLAND

PRINCIPAL INVESTIGATORS: H. LASHINSKY
J. SILVERMAN
R. F. ELLIS

FINAL REPORT

Dr. Herbert Lashinsky, who served as Principal Investigator throughout the bulk of the program, died in April, 1980. With the approval of AFOSR, Drs. Silverman and Ellis assumed responsibility as Principal Investigators for bringing the work to a conclusion. Dr. R. P. Majeski, Research Associate, who was Dr. Lashinsky's principal collaborator in this program, is responsible for most of the technical aspects during the final months and is the chief author of this report.

In its initial stages, before 1976, the research supported by this grant was concerned with the application of theoretical and experimental techniques which are well known in lumped-parameter nonlinear systems (microwave oscillators, etc.), to distributed-parameter nonlinear systems (such as plasmas, fluids and gases). Particular emphasis was given to plasma instabilities, non-linear effects leading to the heating of plasmas, and turbulence phenomena which affect hypersonic plasma flow. This work consisted of a theoretical program supported by experimental work in a low-temperature plasma device known as a Q-machine. The general goals of this initial phase were largely realized both theoretically and experimentally. In the theoretical effort we have developed a modified van der Pol equation, derived a new equation (Lashinsky-Cap) to describe various aperiodic instabliities typical of high-speed flow in fluids and plasmas, and developed a new form of the Mathieu equation, which describes nonlinear effects in the degenerate parametric excitation of plasma waves. Many of these theoretical results have been verified experimentally in the Q-machines

A monograph on the methods of analyzing distributed-parameter systems developed in this program, "Periodic Nonlinear Phenomena", had been nearly completed by Dr. Lashinsky at the time of his death; the monograph is being readied for submission to North Holland Publishing Company.

In recent work, methods developed in the earlier investigations of nonlinear plasma phenomena in this program have been applied to certain experimental and theoretical problems of current interest. In particular, our efforts have recently concentrated on methods for the suppression of plasma instabilities by nonlinear techniques, and on the study of nonlinear mechanisms that lead to the saturation of certain plasma instabilities. In turn, this work has required a detailed investigation of a particular kind of plasma oscillation, the lower-hybrid resonance. This work has also led to certain "spinoff" results which are not immediately associated with the instability-suppression problem. These spinoff results include the observation and analysis of a radio-frequency "transparency" effect in plasmas and the explanation of "frequency-jump" phenomena in nonlinear resonance systems.

We feel that the objectives of this second phase have been largely accomplished. The suppression experiments have been particularly successful. In fact, we have demonstrated the suppression of most of the low-frequency instabilities which may be observed in our experimental device, the Q-machine.

The major results obtained in the second phase of this program (1976 to present) are as follows:

1. <u>The Investigation of Lower-Hybrid Resonances in a Bounded Plasma.</u>

Studies were performed on the identification and frequency of the resonance and the design of an efficient radio-frequency coupler to introduce power into the plasma at the lower-hybrid frequency. This analysis is relevant to the problem of plasma heating by the introduction of radio-frequency power at the lower-hybrid frequency, as well as to the "dither" stabilization of various low frequency plasma instabilities investigated under this program.

This work has led to the publication of "Oscillations of a Bounded Plasma in the Lower-Hybrid Range" by R. A. Gore and H. Lashinsky, Physics of Fluids, 22, 2178(1979), and was further described in Dr. Gore's Ph.D. dissertation "Resonance Oscillations Near the Lower-Hybrid Frequency in a Bounded Plasma on a Strong Magnetic Field".

2. Radio-Frequency Transparency Effect in a Plasma in a Strong Magnetic Field.

The Q-machine used in the experimental component of this program is unique. It is the only plasma device in which the ratio of magnetic field to density can be so high as to satisfy the condition $\omega_{ci} >> \omega_{pi}$, where ω_{ci} is the ion cyclotron frequency and ω_{pi} is the ion plasma frequency. The experimental investigation of this regime led to the observation of a so-called plasma transparency effect, in which electromagnetic waves propagate through the plasma without being affected by it. This effect was the subject of a paper presented at a meeting of the American Physical Society: "Reduction in Radio-Frequency Plasma Absorption at High Magnetic Fields" by H. Lashinsky, R. Gore and J. R. Conrad, Bull. Am. Phys. Soc. 21, 1032 (1976).

These observations may be of interest in describing certain features of pulsar x-ray emission, and could provide a communication window through dense re-entry shock-layer plasmas.

3. Nonlinear Analysis of Plasma Flute Instability.

A form of a well-known plasma instability, the flute instability, has been re-examined by the use of a nonlinear differential equation (Lashinsky-Cap) rather than by means of the dispersion-relation approach, which is conventionally used in plasma work. This approach made it possible to examine the nonlinear time evolution of the instability, which had not been previously accomplished. Since the plasma flute instability is representative of a large class of "convective" instabilities, such as the Rayleigh-Taylor instability, the results obtained in this work can be carried over to the nonlinear time evolution of other instabilities of this general class. In addition, it appears that the results of experiments involving the artificial injection of barium ion clouds into the ionosphere, and the nonlinear description of the so-called equatorial spread-F effect, which plays a role in radio-sounding experiments, can also be formulated in terms of the Lashinsky-Cap equation.

The investigation of the plasma flute instability was the subject of a paper, "Plasma Convection Instability in an Inhomogeneous Magnetic Field" by P. Ottinger, H. Lashinsky and J. Guillory, Physics of Fluids, 21, 798 (1978).

4. Frequency-Jump Analysis of Nonlinear Resonance Systems.

Although this analysis is not a central objective of the program, it is related to the program's general philosophy of describing distributed parameter systems such as plasmas, lasers, fluids, etc. through methods better known for their success in describing lumped parameter systems. We have successfully described nonlinear effects observed in NMR measurements on a target used in high-energy physics experiments in terms of mode competition and the associated frequency jump effects exhibited by nonlinear resonance systems in the following paper: "Nonlinear Mode Interactions and Frequency-Jump effects in a Doubly Tuned Oscillator Configuration" by J. Grun and H. Lashinsky, J. Appl. Phys., 51, 2494 (1980).

5. Stabilization of Low-Frequency Instabilities in Plasma by the Application of a High Frequency Field.

There are two broad classes of stabilization methods utilized in control engineering: (1) closed loop or feedback methods involve a process of measuring the deviation from a specified equilibrium in the system to be stabilized, and applying some force to the system to correct the deviation; (2) open loop methods involve the application of an a priori force to the system which prevents the deviation from equilibrium before it occurs. This program has been concerned with the application of a particular open loop method, known in control engineering as "dither stabilization", to the suppression of various low-frequency plasma instabilities. The method involves the introduction of radio-frequency power at the lower-hybrid frequency to the plasma through an inductive coupler designed earlier in the program. We have been successful in quenching the following instabilities:

a. Collisionless Drift Instability. This instability can cause anomalously rapid loss of plasma (and energy) in fusion devices. Its suppression was reported in "Stabilization of Drift Waves by Lower Hybrid Fields" by R. A. Gore, J. Grun and H. Lashinsky, Phys. Rev. Lett., 40, 1140 (1978).

b. The Current-Driven Electrostatic Ion Cyclotron Instability. This instability is closely related to the drift-cyclotron loss-cone (DCLC) instability, which is thought to be the principal cause of non-classical loss of confined plasma in mirror fusion devices. These results were reported in "Stabilization of the Current-Driven Electrostatic Ion-Cyclotron Instability by Lower-Hybrid Waves" by N.S. Wolf, R. Majeski, H. Lashinsky, V. Tripathi and C. S. Liu, Phys. Rev. Lett., 45, 799 (1980).

c. The Current-Driven Ion Acoustic Instability. This instability is thought to be the source of undesirable oscillations leading to inefficient use of thermionic converters in the generation of power in unattended installations. A paper by Lashinsky and Majeski detailing these results is in preparation.

This program of instability suppression via "dithering" has met with such success that we plant to continue the research with an experiment investigating suppression of the DCLC instability. These investigations are to be carried out by Drs. R. F. Ellis and R. P. Majeski.

6. Periodic Pulling and Power Line Interactions with Ionospheric Waves.

Recently, investigations of both natural and manmade waves in the ionosphere which mirror back and forth between Siple Station in Antarctica and Roberval in

Canada have shown that the waves are affected by phenomena at frequencies that correspond to harmonics of power line frequencies, due to interactions with the Canadian power line grid. Among the effects observed are nonlinear frequency pulling effects and the generation of sidebands; these are phenomena observed in the earlier phase of this program in conjunction with the mechanism known as periodic pulling. We have found that many of these effects are well-described by a formalism developed to explain corresponding phenomena in the Q-machine. The results have been reported in "Power Line Radiation: Evidence of van der Pol Oscillations in the Magnetosphere" by H. Lashinsky, T. J. Rosenberg, and D. L. Detrick, Geophys. Rev. Lett., 7, 837 (1980).

7. Plasma Turbulence and Intrinsic Stochasticity.

Ongoing investigations of turbulence in plasmas and fluids indicate that this phenomenon may be due to nonlinear interactions among a small number of unstable modes in a system. Previously it had been attributed to an indeterminably large number of unstable modes at incommensurate frequencies. Earlier work performed in this program, again in connection with the phenomenon of periodic pulling, is relevant to this new model of turbulence and has been re-examined in this light. Periodic pulling is the name given to chaotic (i.e. turbulent) behavior of an unstable van der Pol oscillator which is on the verge of being synchronized by another mode. Our studies show that this mechanism can produce a turbulent wave spectrum through the interaction of a small number of discrete, unstable modes, which is in accordance with the newly emerging picture of turbulent phenomena. These results were presented by Dr. Lashinsky at a conference in a paper, "Turbulence in a Plasma with Discrete Modes". The proceedings were published in Intrinsic Stochasticity in Plasmas, Editions de Physique, Orsay, France, p. 425 (1979).

8. Effect of Fluctuations on the Onset of a Degenerate Parametic Plasma Oscillation.

In carrying out experiments on parametrically excited ion-acoustic waves in the Q-machine it was observed that the onset of oscillations is sensitive to thermal fluctuations in the system. These oscillations are excited by turning on the pump signal "instantaneously". It is found, however, that the oscillation does not start immediately. Rather one observes a random delay, which depends on the fluctuations in the plasma at the time the pump is turned on. The effect is observed in the Q-machine because the thermal capacity of the plasma in this device is so low that it is sensitive to small fluctuations. To the best of our knowledge, this effect has not been observed in any other experiment on parametric oscillations, in plasmas or otherwise.

The ability to see the effect of fluctuations of this kind is important for the following reason. In the last decade it has been found that a detailed analogy exists between 1) the onset of an instability in a nonequilibrium system like a plasma and 2) the onset of a phase transition in a system in thermal equilibrium e.g., critical opalescence. If this analogy were complete in every detail it would be of fundamental importance in physics. The one area in which the analogy has not been established is in the relation between the distribution functions for fluctuations in the two kinds of systems. The fact that fluctuations have a strong observable effect in the Q-machine plasma means that a detailed experiment can be carried out to measure the distribution function of the fluctuations at the onset of the instability. Drs. Ellis and Majeski have completed the design and construction of a data acquisition system to make online measurements of the distribution function. Experimental work is in progress.

Responsibility for future work in this field will shift to the Laboratory for Plasma and Fusion Energy Research where it will be led by Dr. Richard Ellis.

PUBLICATIONS AND CONFERENCE PRESENTATIONS

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14. "Resonance Oscillations Near the Lower-Hybrid Frequency in a Bounded Plasma in a Strong Magnetic Field" by Robert A. Gore, Ph.D. dissertation, University of Maryland, (February 1978).